
# Aircraft Airworthiness and Sustainment Conference

## Space Shuttle Main Propulsion System Gaseous Hydrogen Flow Control Valve Poppet Failure

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# Agenda:

Section 1: Failure over-view and MPS system familiarization

Section 2: M&P Investigation - Don Sueme

Section 3: Particle Impact Testing/Analysis - Justin Kerr

Section 4: Eddy Current Inspection - Ajay Koshti

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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Observation:

- During STS-126 (OV105) ascent phase, the Main Propulsion System (MPS) engine #2 Gaseous Hydrogen (GH2) flow control valve (FCV) LV57 appeared to transition from low flow towards high flow position without being commanded to do so
- Upon removal post-flight, the FCV poppet head was found to be damaged (~87 degrees of the poppet head circumference broken-off)

Concerns:

- Depending on the time of failure(s), number of FCV poppet failures, and/or severity of this type of failure, it could result in:
  - LH2 external tank over-press causing overboard venting / fire hazard
  - LH2 external tank under-press causing External Tank structural failure or low Space Shuttle Main Engine turbo pump Net Positive Suction Pressure
  - Downstream component/line damage or blockage
    - Line rupture could result in ET under-press or venting / fire hazard in aft fuselage

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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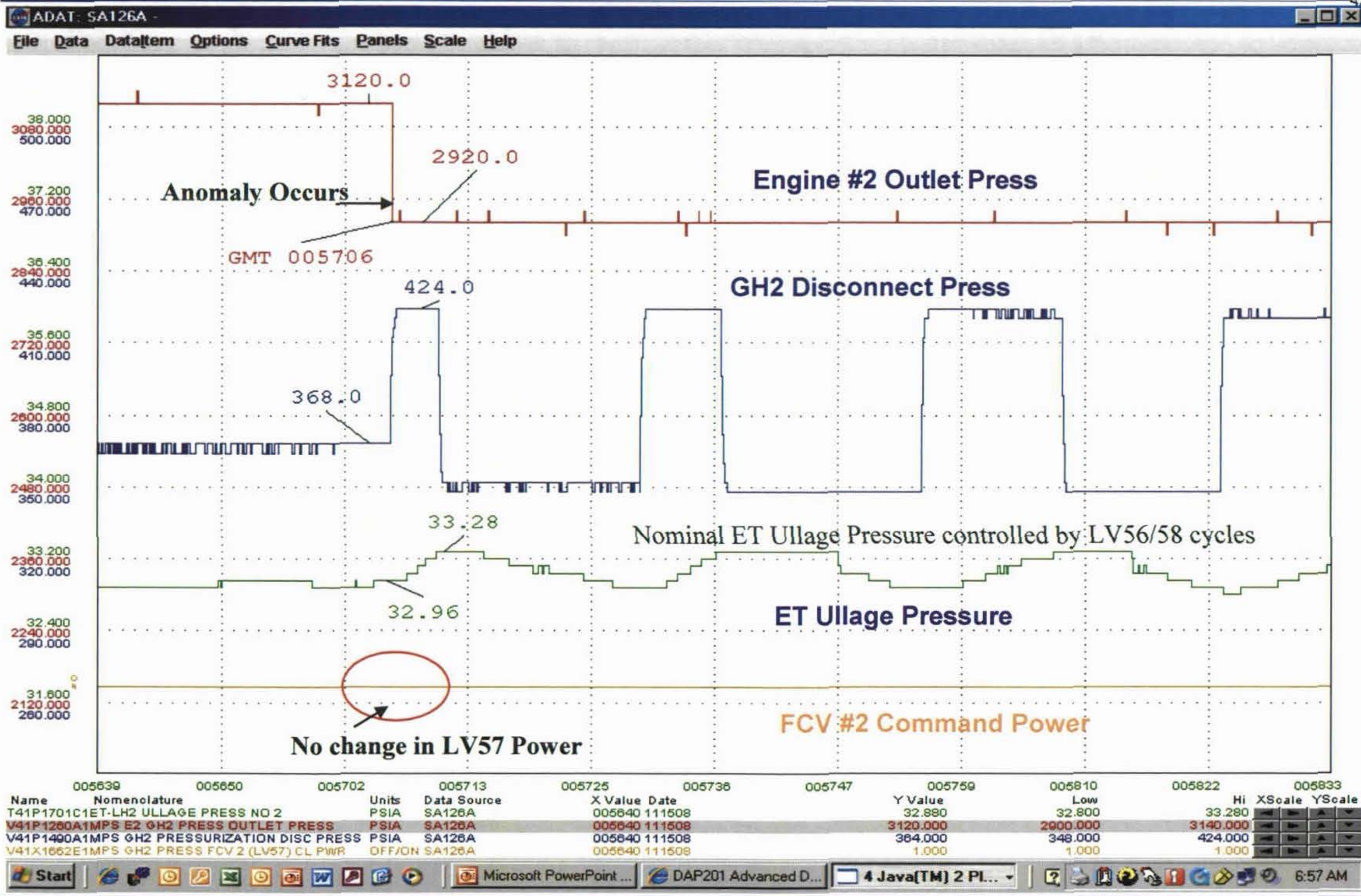

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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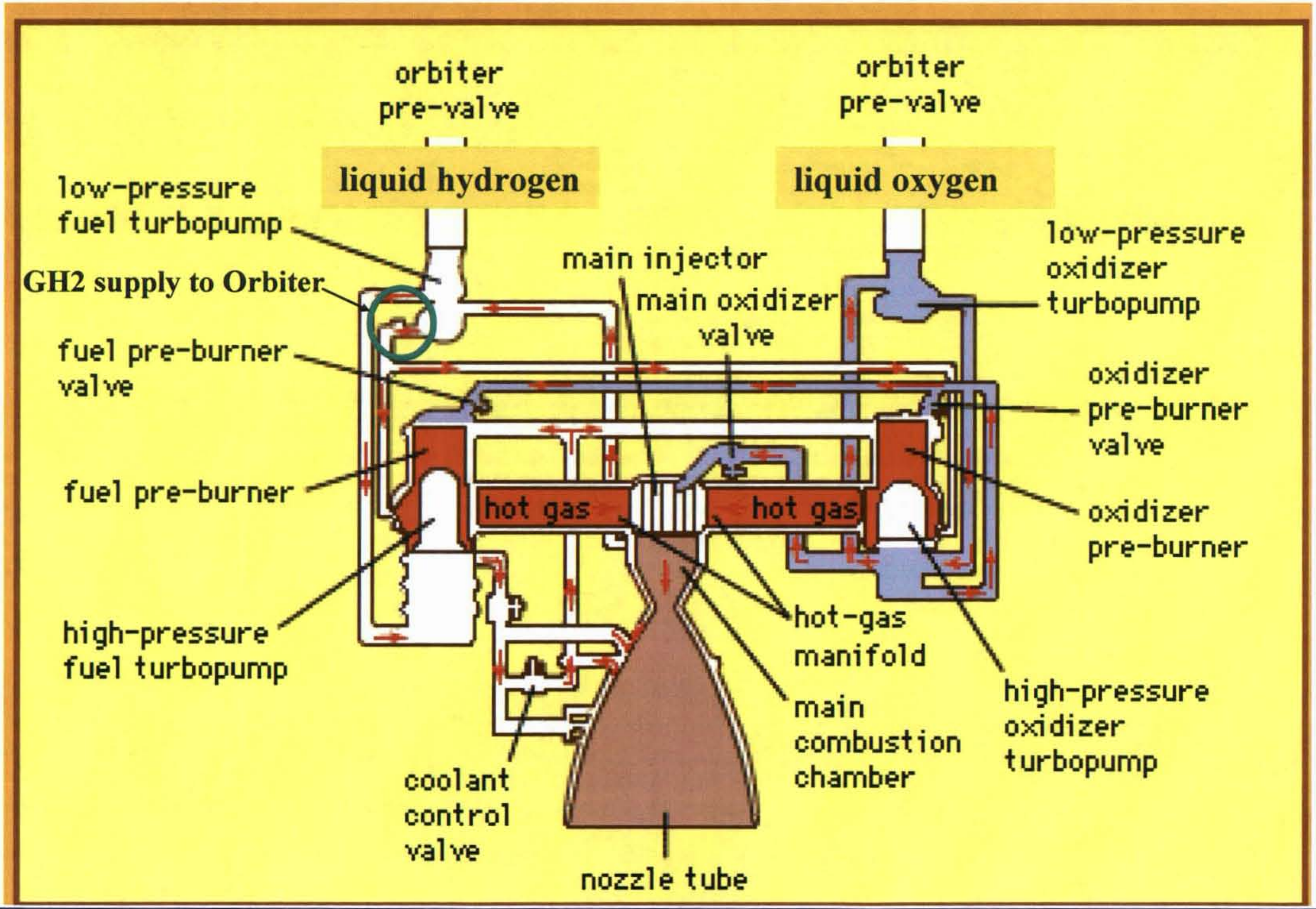
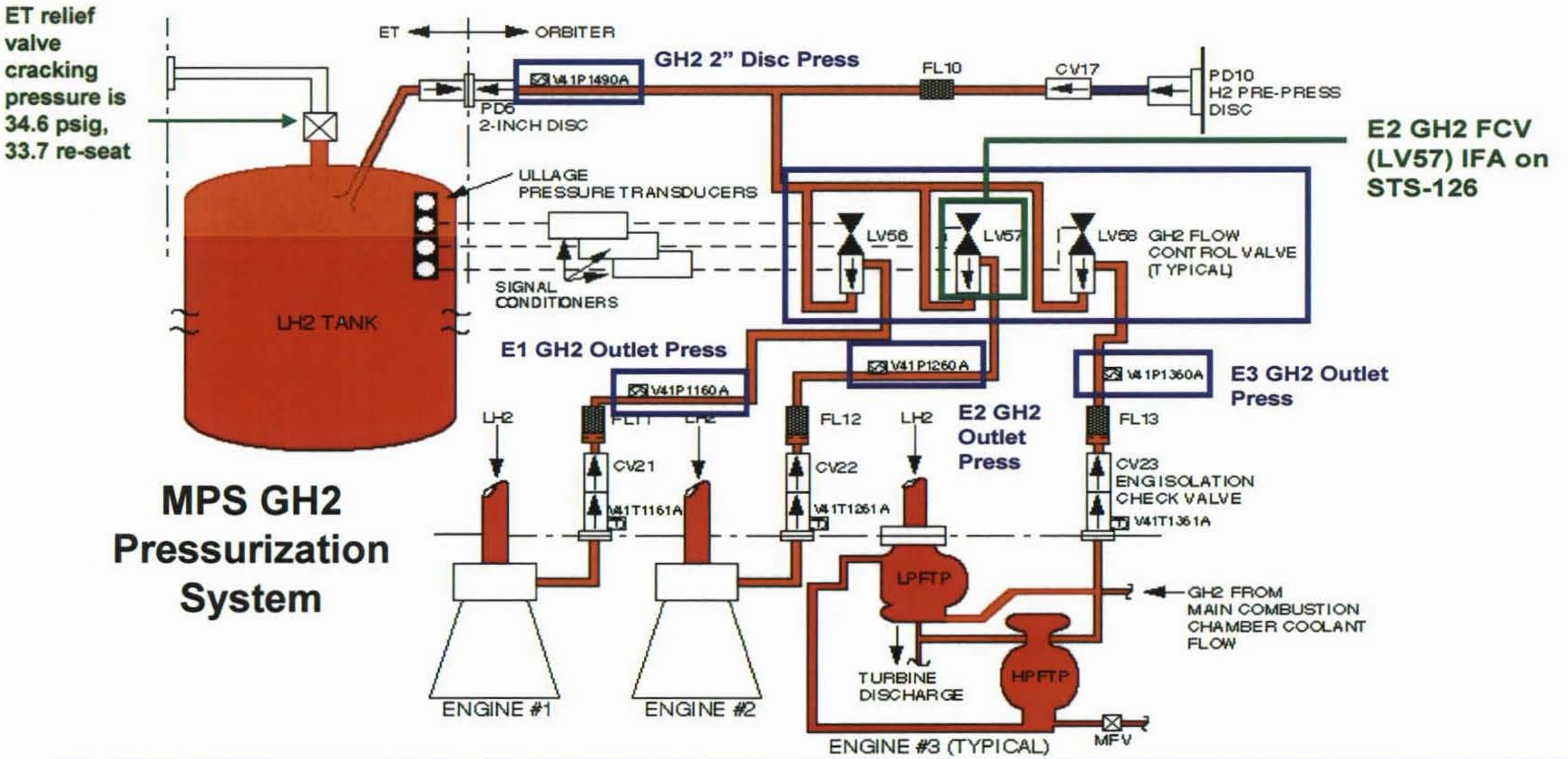


# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary



## Background - MPS GH2 Pressurization System & FCV Overview:

- FCVs (one per engine) provide GH2 pressurant to ET LH2 tank in flight
- Commanded ON/OFF by corresponding ullage pressure signal conditioner
  - ON (low flow) when ET ullage press exceeds 33.2 psia, OFF (hi flow) when press drops below 32.8 psia

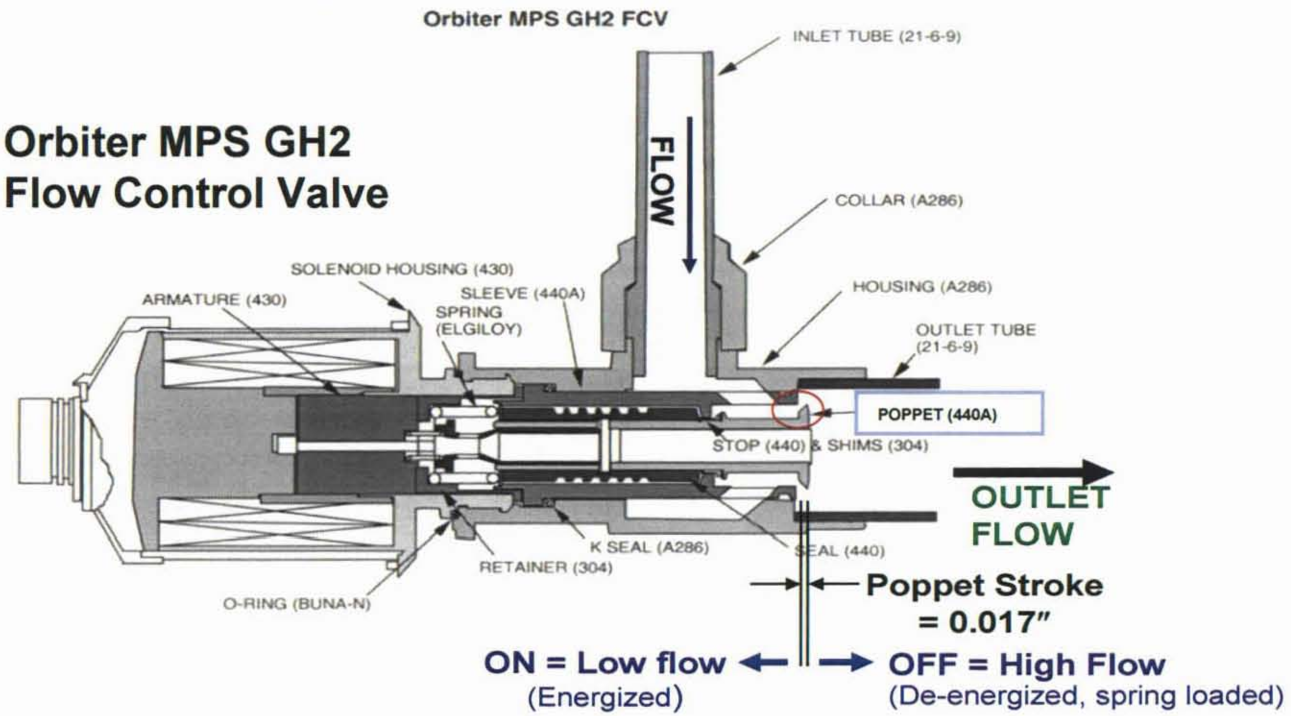



**MPS GH2 Pressurization System**

## Background - MPS GH2 Pressurization System & FCV Overview:

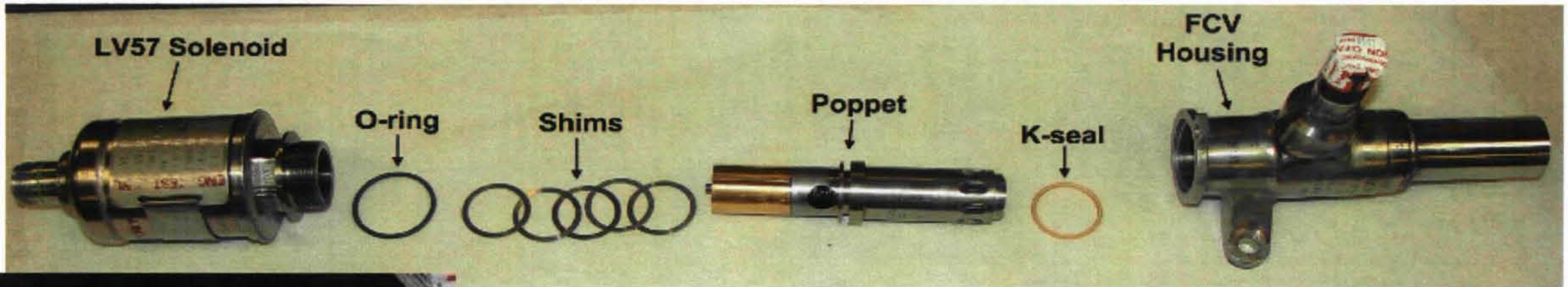
- Solenoid operated valves with spring return - two positions: ON/OFF
  - ON = Solenoid energized/low flow – poppet closes against spring & flow forces
  - OFF = Solenoid de-energized/high flow - poppet opens due to spring & flow forces
- FCVs are shimmed to provide 31% (energized) and 70% (de-energized) flow

**Orbiter MPS GH2 Flow Control Valve**

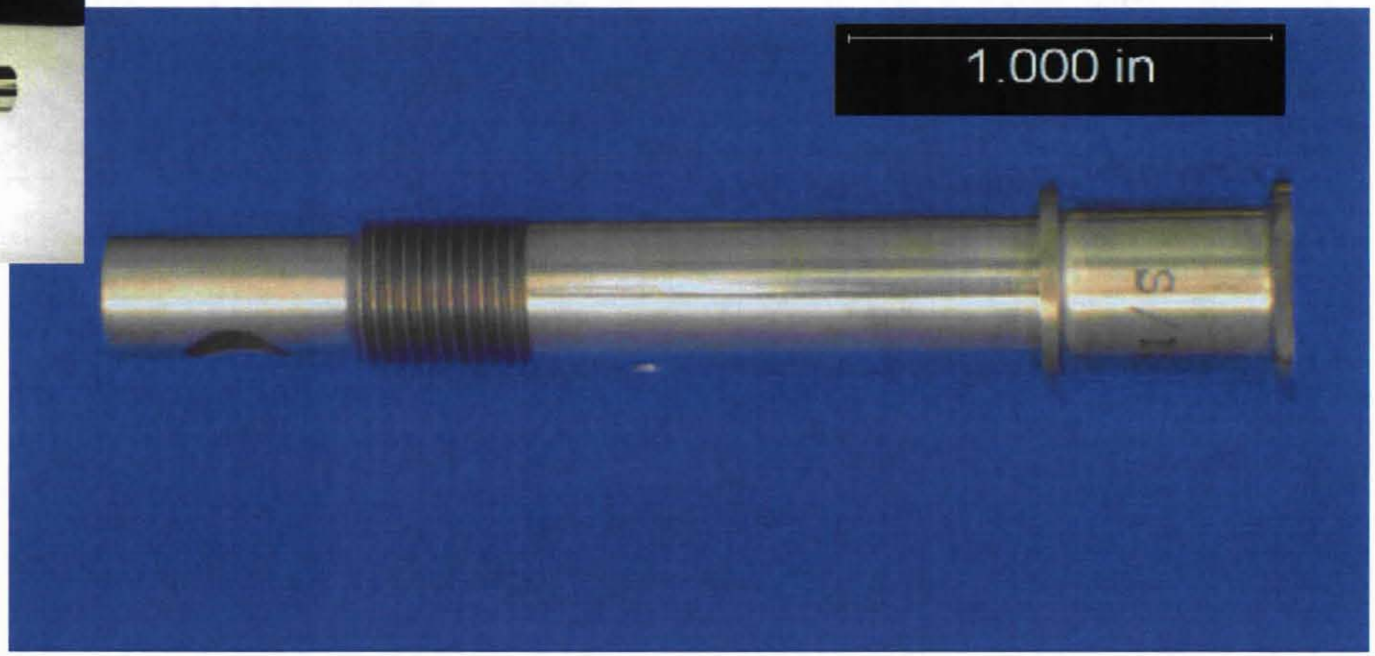


# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary






MPS GH2 Flow Control Valve and Poppet



# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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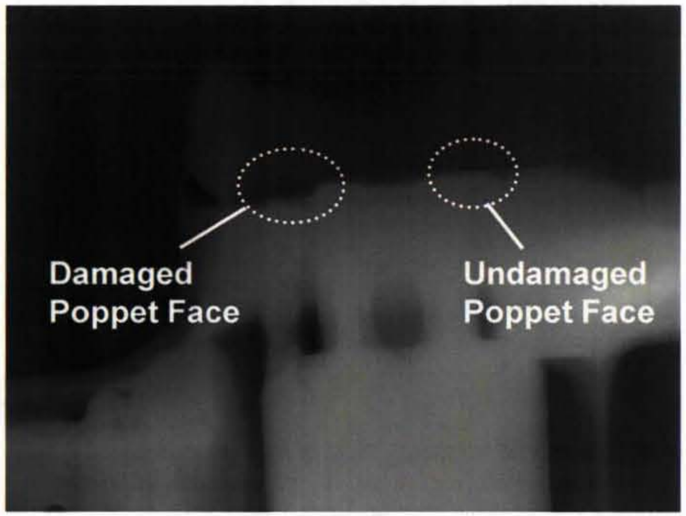
## Post-Flight Inspections of the Failed Poppet:

- Post flight X-ray inspections of FCV #2 (LV57) were performed on the vehicle, and revealed damage to the solenoid poppet nose
  - Missing section of material (~ 20% of circumference) was detectable
- LV57 (S/N 1005) removed from the vehicle and shipped to the vendor (Vacco) for disassembly prior to failure analysis at HB
  - Damaged poppet obvious upon removal, confirming X-ray indications
  - Damaged area was aligned with valve inlet tube (significance not known)




**FCV #2 On-Vehicle X-Ray**

**Valve Poppet Following Removal**

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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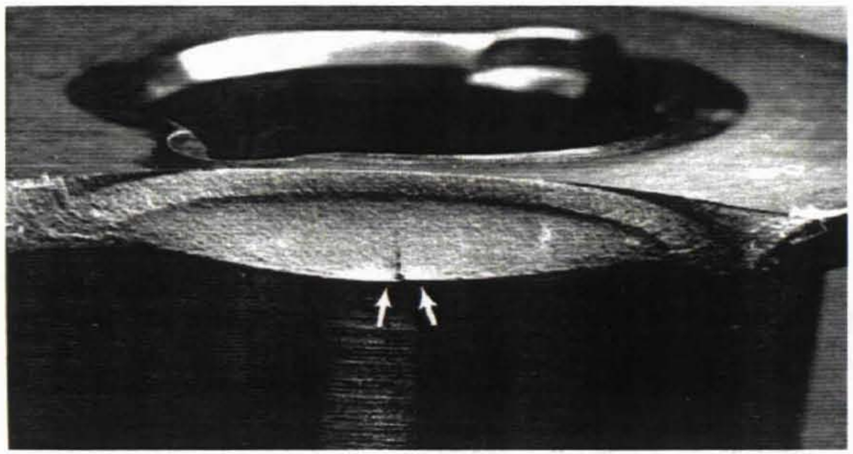
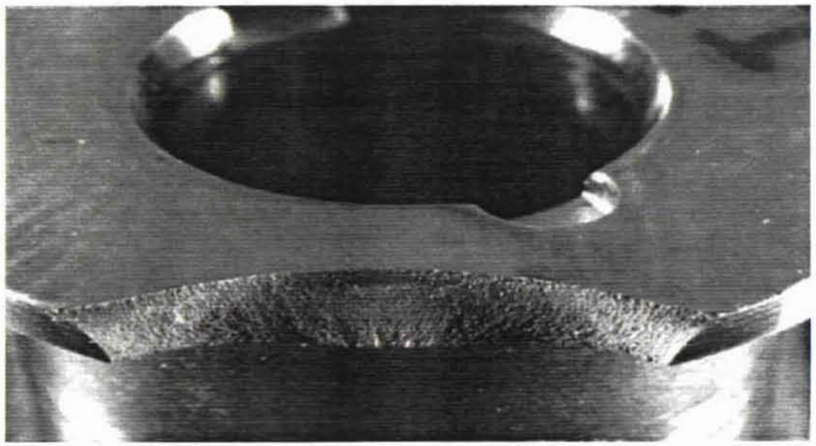
## MPS FCV Poppet Failure History:

- In 1990, two poppet failures (from a shipset of new FCVs being manufactured for OV-105 build) occurred during acceptance testing in GH2 flow test
- M&P fractography of the two previous failures found indications that the failures initiated in fatigue but failed primarily by overload
  - Crack initiations indicated low stress/high cycle
  - Poppet break concluded to be induced by high stress
- Multiple changes were implemented



**Fracture of 1st poppet (type -0361)**



**Fracture of 2nd poppet ( type -0361)**

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

## Background - FCV Modification History

- Post 1990 poppet failures, -0361 FCV poppet drawing changes were incorporated
  - Eliminated 440C as an acceptable alternate material for poppet - only 440A was used from that point forward
  - Poppet heat treatment was altered & temper cycle added to reduce possibility of embrittlement
    - Recent investigation showed this change to be somewhat ambiguous (drawing not clear) and several heat treat processes were actually used in subsequent poppet builds
  - Non destructive examination NDE (dye penetrant) was added

- Following recent 2008 poppet failure, -1301 FCV poppet drawing updated with following changes
  - M&P community agreed upon heat treatment process
    - Drawing ambiguity eliminated
  - Polish/etch of critical radius area
  - Scanning Electron Microscope inspections added
  - Eddy current inspections added

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

## Background - FCV Modification History (Other Significant Issues)

- New fleet -1301 FCVs implemented in 1997-98 to reduce occurrences of sluggish FCV operation due to contamination
  - New poppets, sleeves, and labyrinth seals (with tighter process controls) to minimize self-generated contamination
  - System filters were added upstream of the FCVs (between the engine interface and the FCV inlet) and in the gaseous helium prepress line to mitigate potential contamination from the SSMEs and from the ground supplied prepress (GSE)
  - Manifold re-configured to change the FCV orientation such that the valve was not a collection point for contamination in the vertical orientation
- FCVs remained installed and functioning with no operational issues from 1998 until 2005
- O-ring leak (during STS-114 pad testing) resulted in requirement to remove FCVs for o-ring replacement due to age/environment induced embrittlement

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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STS-126 failed FCV (S/N1005) history

- Valve had flown a total of 11 flights
  - Originally installed in OV-105 for 8 flights in the E1 LV56 position
  - FCV removed for refurbishment (o-ring replacement) & installed in OV-105 E2 LV57 position
  - FCV had 3 additional flights before poppet failure on STS-126

- Valve had relatively low cycle count (94) compared to other fleet valves
  - FCV qualified for 4600 energized/de-energized cycles
  - Review of both flight and part history did not reveal any data that identifies this poppet (S/N 0047) as an outlier

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary



## Failure Summary

- M&P investigations determined the poppet failed as a result of high cycle fatigue loading (to be coverer in greater detail in following presentation
- The MPS GH2 operating environment/pressure loading cycles (typically <15 cycles per flight) did not support a high cycle fatigue failure condition
- Extensive computational fluids dynamics (CFD) modeling and structural modes analysis was performed. The combination of CFD acoustic mode predictions, with the intersection of structural modes, and their presence in the acoustic emission flow test data provides two areas of interest for damage consideration even though the state of the art analyses conducted to date does not predict initiation:
  - **GH2** flight and test environment resulting in a potential 109 Khz resonance
  - **GN2** full stroke force balance testing at the vendor during valve build-up and flight stroke shimming
- Most probable cause for the failure was identified as being GN2 ground test induced 'starter' cracks that gradually grew to failure over the course of the 11 flights of this valve

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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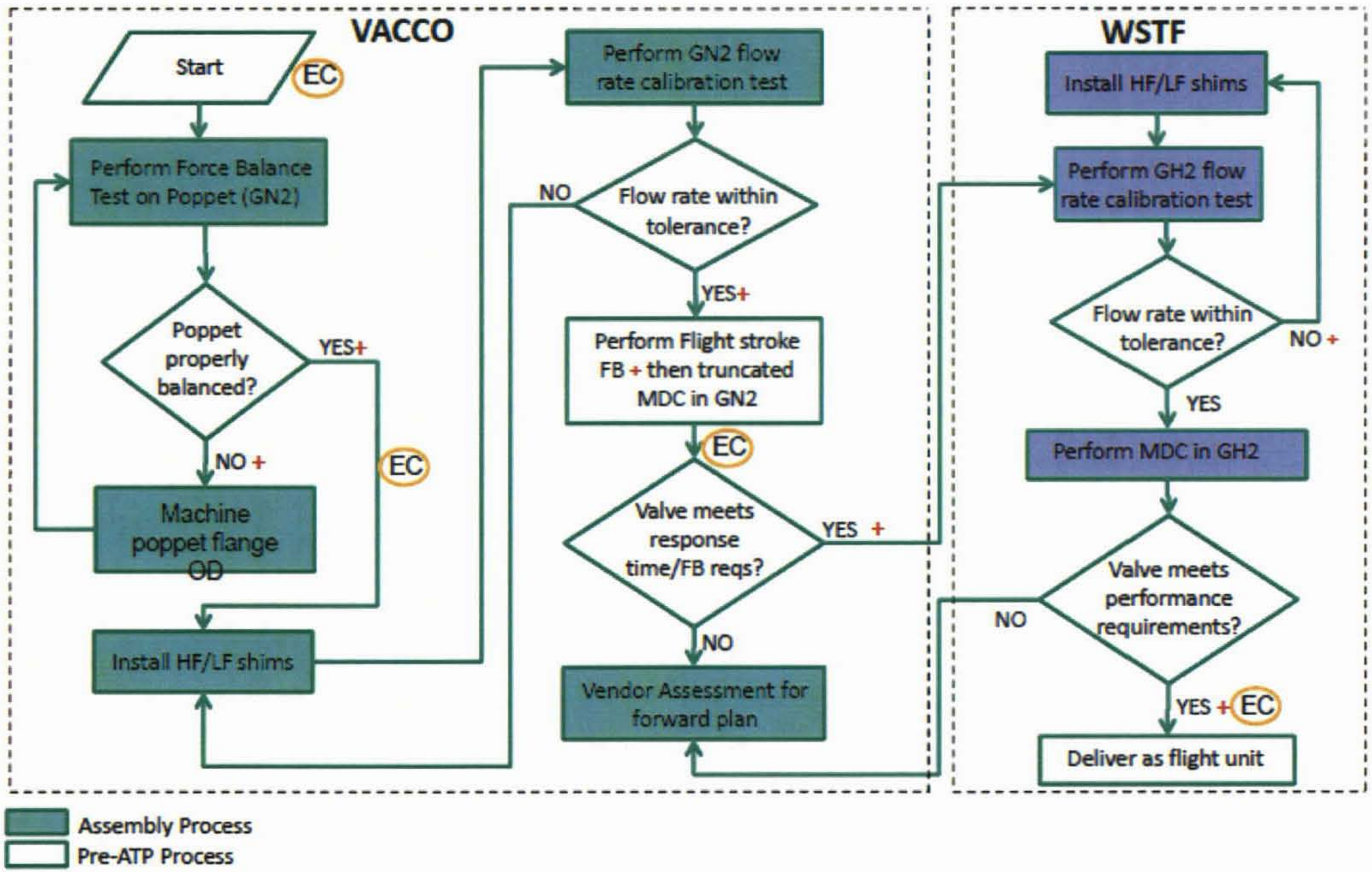
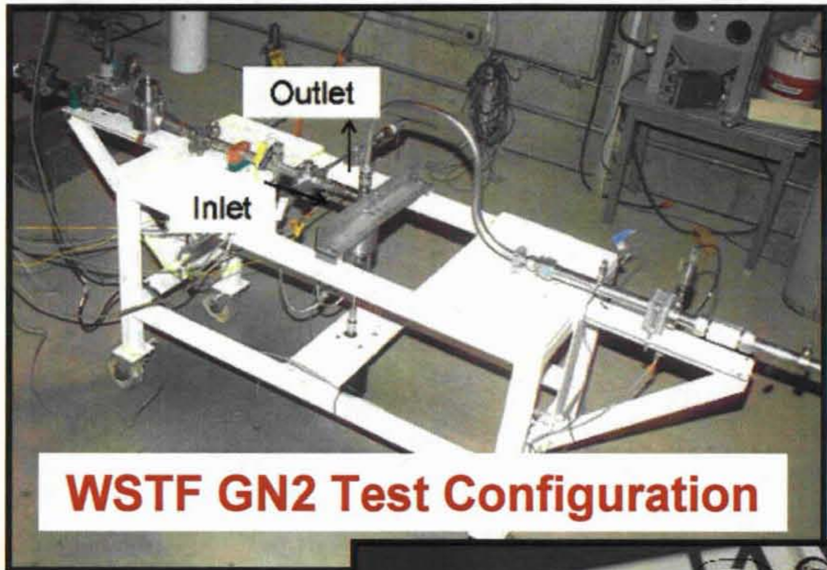
## FCV Assembly/ATP Process Flow

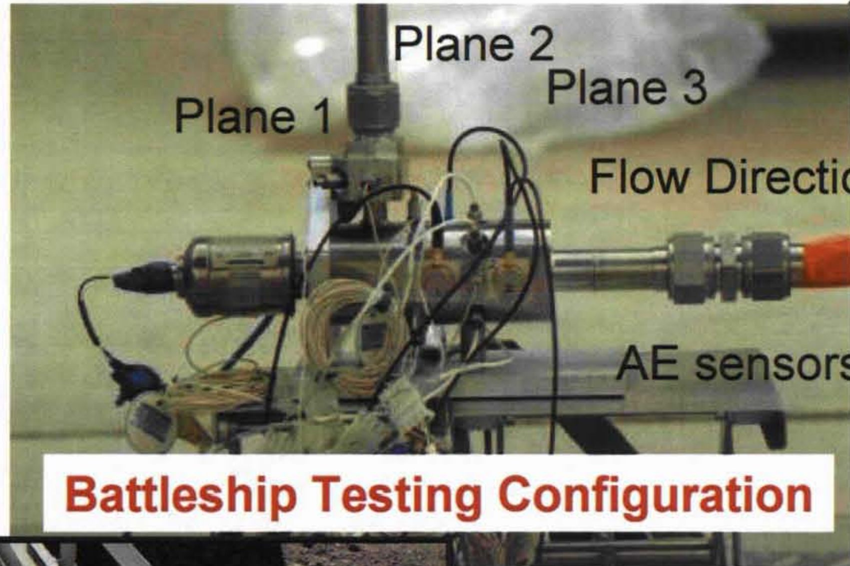


# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

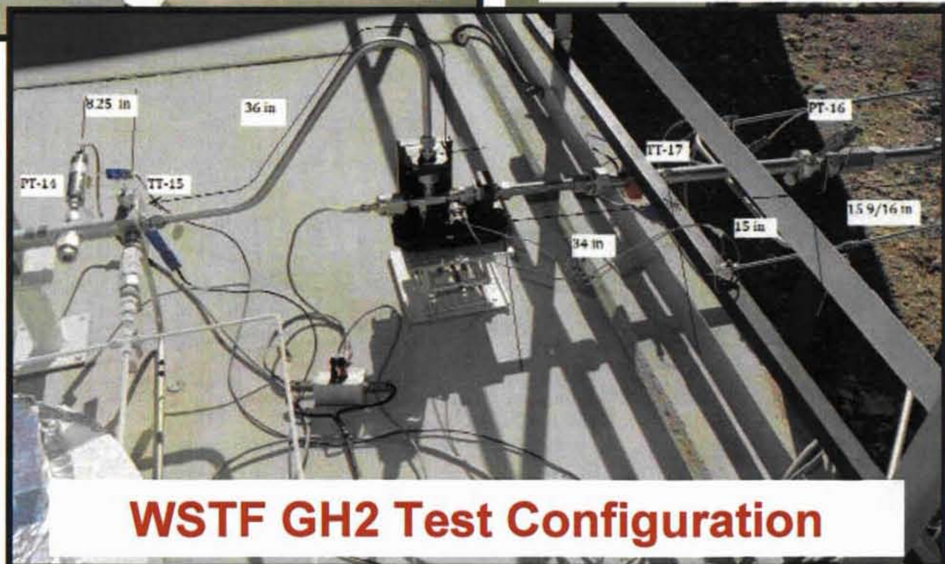




WSTF GN2 Test Configuration



Battleship Testing Configuration



WSTF GH2 Test Configuration

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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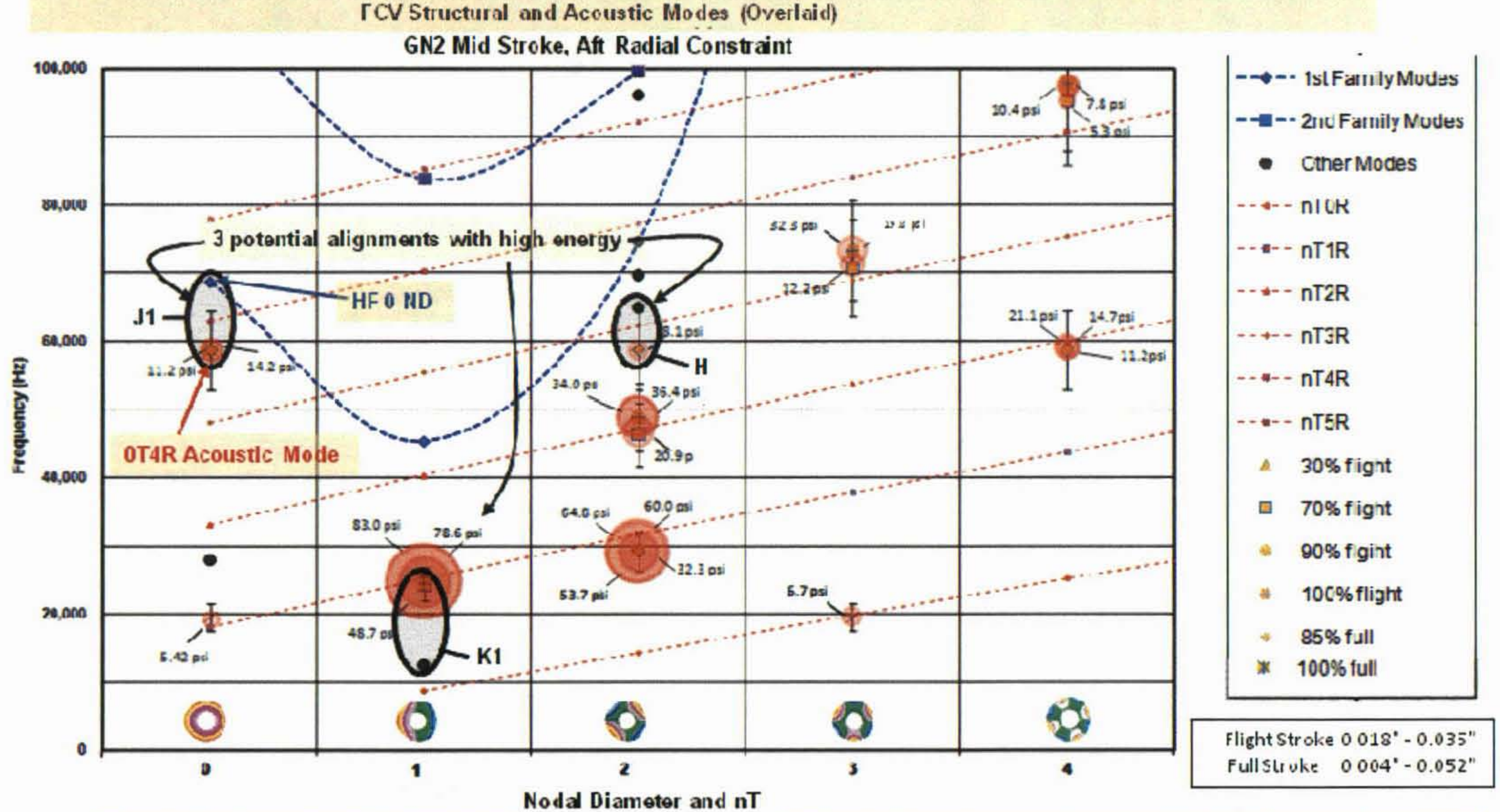
Acoustic mode mean pressures are indicated by size of orange filled circles. GN2 pressures are generally higher than GH2.




**Note: At 100% full stroke, the poppet seats and structural modes shift from the unseated condition. The 0-ND structural mode at 56 kHz shifted down from 69 kHz prior to seating, crossing through the 0T1R acoustic mode at 59 kHz.**

C. Fulcher/ER41 Jacobs

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

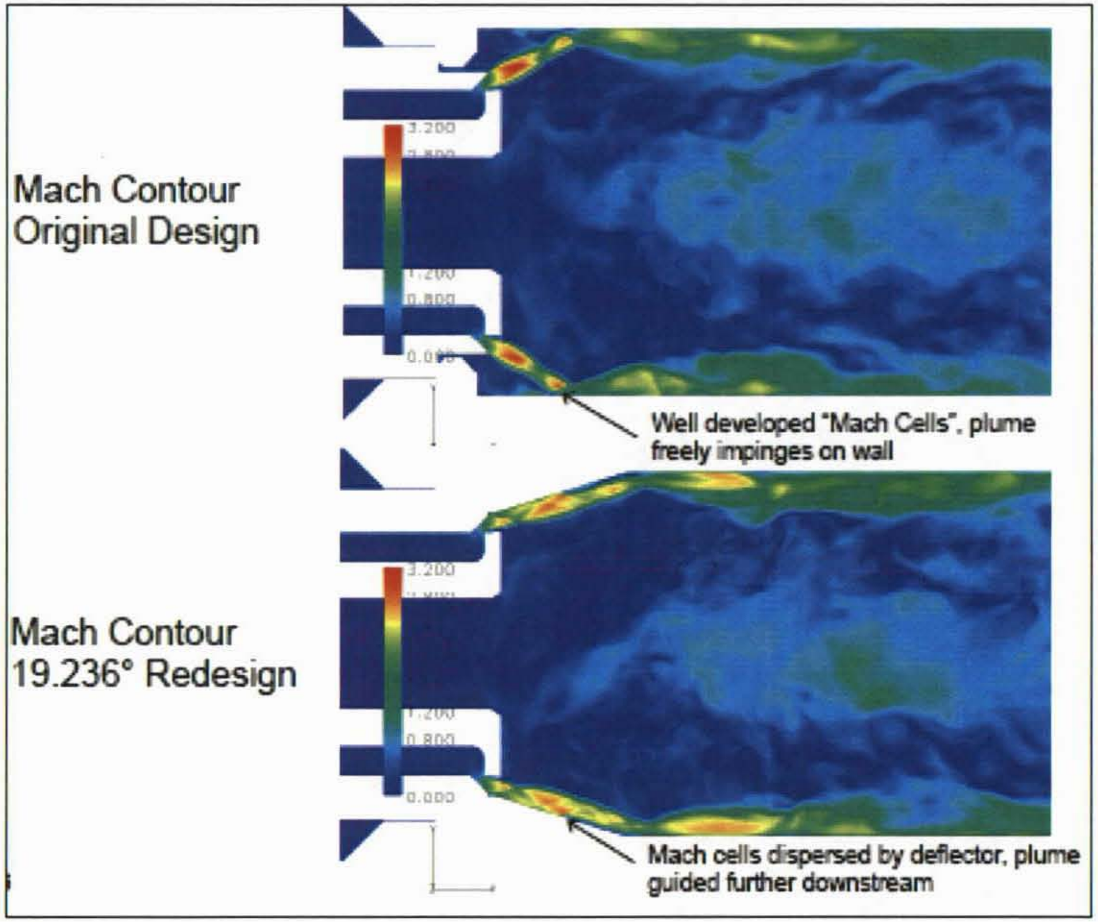
## Design modifications considered

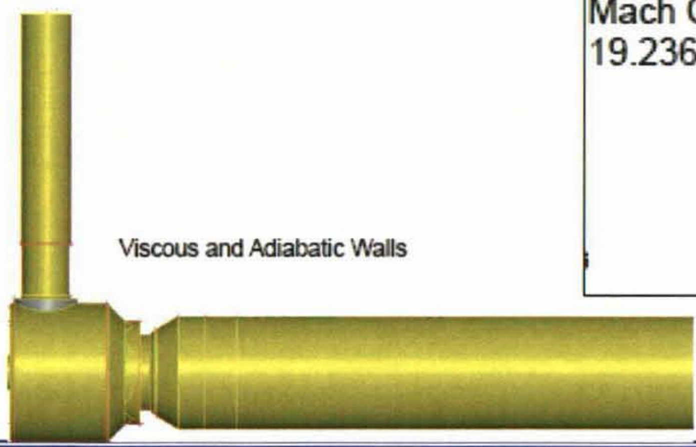
- Modifications to either the FCV or within the MPS system were considered to address the broken poppet issue
  - Three design changes were considered to control poppet breakage
    - Poppet redesign – intended to alter the acoustic environment, reducing driving force, while adding material to make poppet more resistant to breakage
    - Poppet material change – 440A known to be poor choice for high pressure H2 environment
    - FCV outlet tube change - to diverging flare angle has been shown by CFD to reduce dynamic pressure component
  - Concepts to minimize effects of broken poppet within the system
    - Augment MPS system to handle impact (i.e., beef up elbows)
    - Particle traps at 2" flange (i.e., witch's hat)
    - External reinforcement to existing lines
- Rather than a design change, emphasis was placed on improving NDE of poppets towards an "inspect and fly" flight rationale
  - Risk in implementing design changes without knowing root cause or understanding the environment
  - Limited poppet assets to support destructive testing
  - Program accepted risk of additional poppet failure
  - Poppets selected for FCV installation have undergone best NDE techniques

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary



Per CFD analysis, 19.2 degree diverging outlet tube reduces high velocity impingement on wall, minimizing energy transmitted to poppet face Testing would be required to verify poppet flow balance can be achieved





Viscous and Adiabatic Walls

## ET Over-press/Venting

- Integration team analyzed relationship between the size of poppet crack & effects on ET venting
  - Both single & two poppet failure cases included in venting analysis
  - Analysis constructed with STS-119 data – includes SSME specific operating performance parameters
  - Accounts for $\pm 1\ \sigma$ dispersions

- For single poppet failure, no risk of ET venting for poppet particle sizes up to 125 degrees (see Figure 2.)
  - STS-126 poppet failure ~90 degrees
  - Bounding fracture analysis indicates the worst case poppet liberation size to be ~125 degrees

- For two poppet failures, low risk of ET venting (see Figure 3.)
  - Case 1. - two poppets of STS-126 size (~90 degrees) must fail between SSME start (T-6 seconds) to T+2 seconds
  - Case 2. - for poppet failures 1.25 x STS-126 size (~115 degress), two poppets must fail between T-6 seconds & T+55 seconds

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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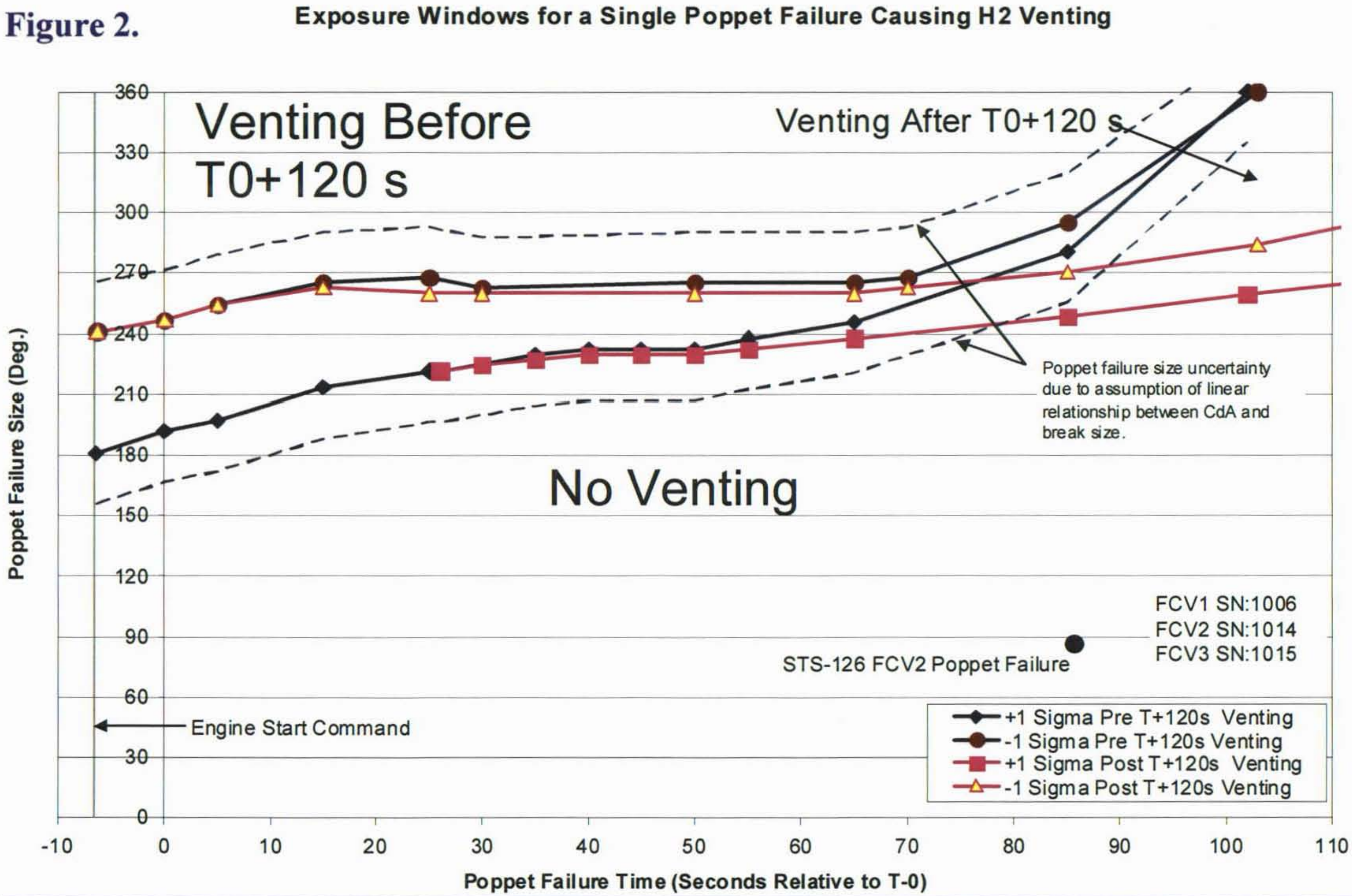
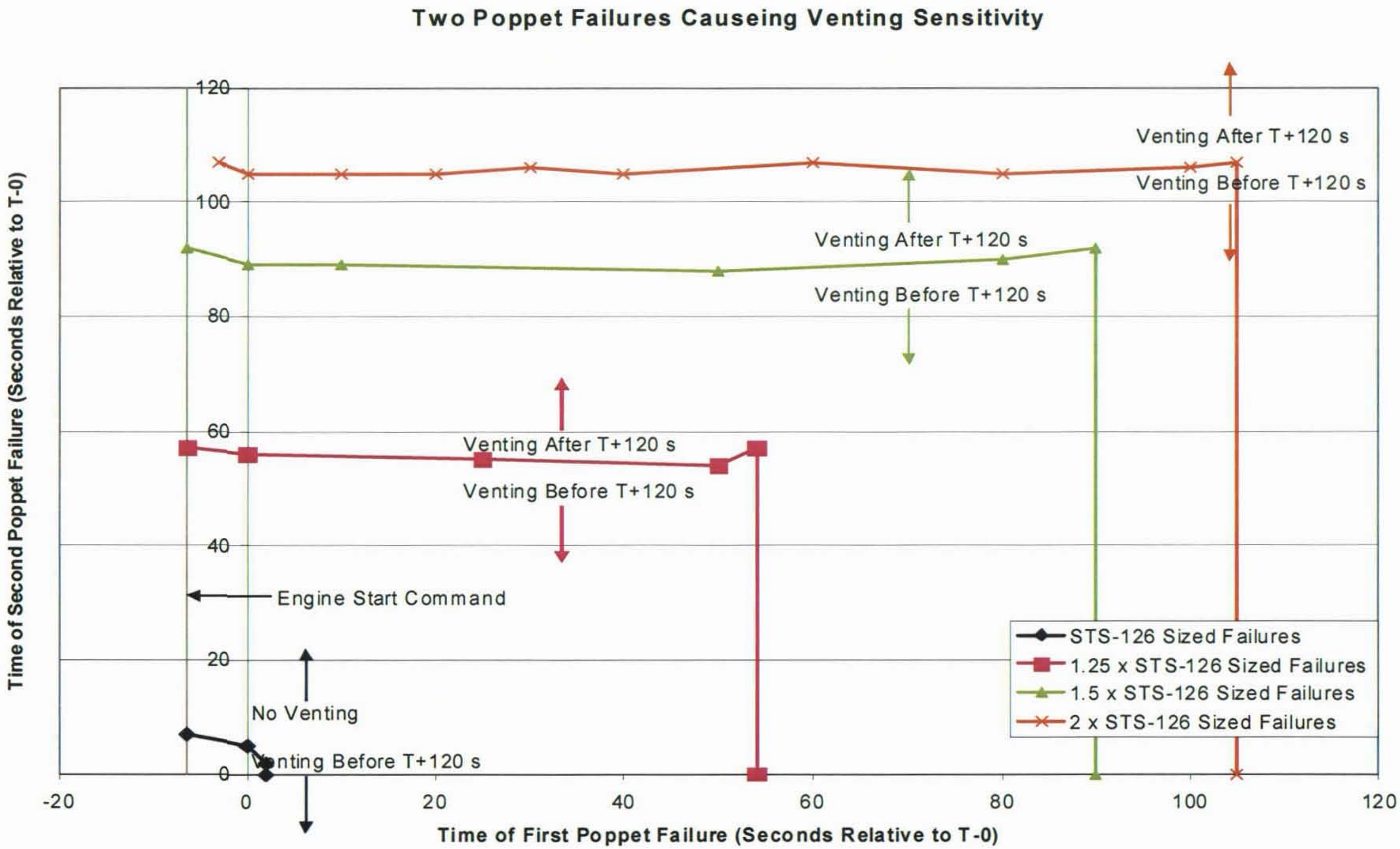
**Figure 2.**



# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary





# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

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## MPS Gaseous Oxygen (GO2) FCV Implications:

- GO2 FCVs have similar poppet design but key design, system operating parameters, and flight history differences exist
  - No previous failures of a GO2 FCV poppet
  - GO2 poppet material Monel, which is a more ductile and tougher material than 440A stainless
  - GO2 valves are fully shimmed (fixed orifices) and do not cycle
  - Operating environment is significantly different
    - Commodity difference (GO2 vs GH2 fluid)
    - System pressures (~3500 psia vs ~3100 psia)
    - Fluid flow rates (1.9 lb/sec vs 0.73 lb/sec)
    - System temperatures (400F vs ~ambient)
    - Significantly lower fluid velocities (104 ft/sec vs 447 ft/sec)
- CFD modeling of the MPS GO2 FCV environment concluded/predicted no coupling of the acoustic and structural modes exist
- Conclusion reached that GO2 FCV poppet failure not a concern

## Flight Rationale:

- Likelihood of a poppet failure in flight is low
  - FCV poppets installed for each flight are crack-free within the limits of the NDE capability ( improved eddy current criteria)
  - Flight history indicates that poppets with cracks within EC criteria are unlikely to grow to failure in a single flight
    - Combination of fractography, fracture analysis, and flight history suggests that small cracks would likely require some number of flights to grow to failure
    - For an out of family resonance case, possible for crack to grow to failure in a single flight
      - Flight history and fractography show resonance is unlikely
  - Bounding analysis based on engineering judgment of fracture experts predicts a maximum particle release of 125 degrees
    - Unique coupled resonance failures result in liberation of smaller particles (less than 90 degrees)

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary



Flight Rationale (continued):

- Consequences of Poppet Failure
  - ET venting analysis shows no ET venting for a single poppet failure (up to 170 degrees) even if that failure occurs as early as engine start
    - Venting prior to 120 seconds requires two 125 degree poppet failures in the first 90 seconds
  - ET under-pressurization analysis shows that the hole size in MPS/ET GH2 line required to under-press the tank is 60 times larger than the biggest damage created during impact testing
  - Orbiter aft compartment over-pressurization analysis shows that the hole size required for failure at liftoff is 8 times larger than the biggest damage created during particle impact testing
  - Orbiter flammability analysis indicates that damage created during impact testing is comparable to that required to exceed concentration limits (Combustion requires oxygen source and ignition source to also exist)
  - Monte Carlo probabilistic risk assessment of Orbiter and ET particle impact consequences shows a low risk of damage confirming the analysis results

# MPS GH2 Flow Control Valve Poppet Failure Investigation Summary

## Summary

- Strong flight rationale for FCV poppets as a result of all the troubleshooting & failure analysis conducted
  - Testing & analysis indicates very small chance that particle will be liberated with poppets installed per EC requirements
  - In the event of a particle liberated, size within limits of impact capability
  - Risk of ET venting very small window
  - Every flight inspections of FCV poppets post flight ensures health of FCVs installed for flight